Development of Novel Sintered Carbon Ore Building Materials

DE-FE0032083

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Microbeam Technologies Inc.

U.S. Department of Energy

National Energy Technology Laboratory

Resource Sustainability Project Review Meeting

April 2-4, 2024

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Outline

- Project Overview
- Technology Background
- Technical Approach and Project Scope
- Progress and Current Status of Project
- Plans for Future Testing, Development, and Commercialization
- Summary

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Project Overview

- Period of Performance: 10/01/2021 through 02/29/2024
- Develop value-added products from carbon ore
- Carbon ore building materials will contain ≥70 wt.% carbon and ≥51 wt.% of carbon from carbon ore
- Demonstrate the ability to produce Sintered Carbon Ore Building Materials (SCBM)
- Ultimately to produce 5-10 bricks per day
- Complete a Technical and Economic Analysis (TEA), a Technology Gap Analysis, and a Life Cycle Analysis (LCA) on the SCBM process
- Create a conceptual design of a carbon-based building using LIG2 products

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Project Overview

- Total project cost: $649,407
- DOE: $517,702
  - Award No. DE-FE0032083
- Cost share: $131,705
  - MTI: $10,200
  - UND: $16,505
  - NACC: $42,500
  - NDIC: $62,500

Technology Background

- Builds on past work conducted by MTI and UND
  - Showing carbonaceous materials can be designed using controlled pyrolysis
  - Tailorable properties
  - Addition of biofibers enhanced the mechanical strength
  - Properties of low ranked carbon-ore and waste carbon-ore
- UND and MTI have performed laboratory-scale testing and analysis on sintered carbon-ore and additive blends
- Scanning electron microscope (SEM) analysis of samples show that the carbon-ore particles are well-bonded to the additive binder

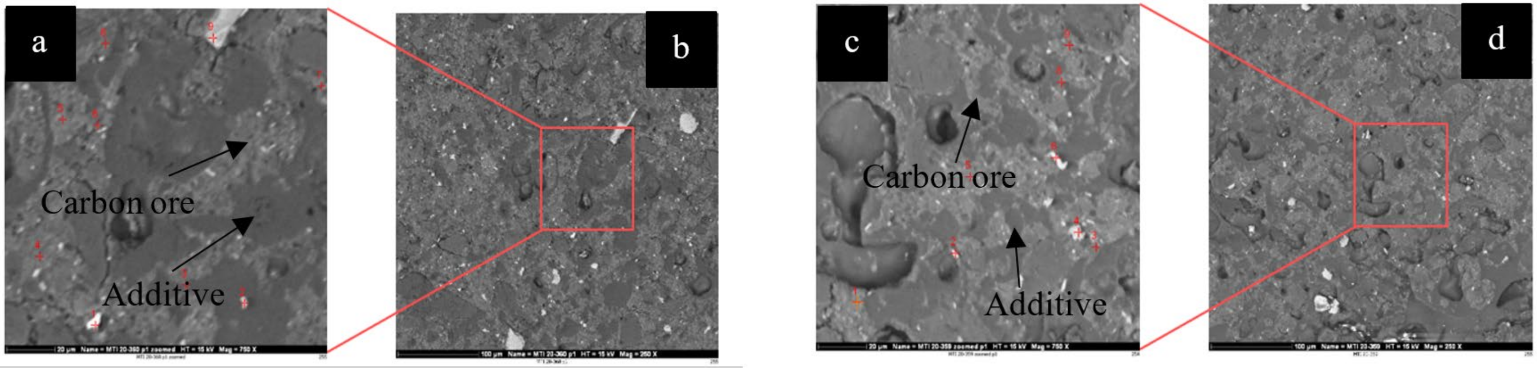

Figure 1: SEM micrographs of (a-b) REE extracted carbon-ore (50 wt.%)-Additive #1 (50 wt.%), (c-d) REE extracted carbon-ore (50 wt.%)-Additive #1 (25 wt.%) after sintering

Technology Background

- Based on the sintering of lignite carbon-ore particles with additives at relatively low temperatures (<500°C)
- During heating, the pyrolyzed carbon-ore and additive interact as a result of sintering with a reactive liquid phase
- Laboratory compressive strength measurements show this technology can produce carbon-ore composites with strengths exceeding the ASTM physical requirements for various types of brick[1]
- The primary product of SCBM technology will be producing LIG2 standard bricks
  - With capability to produce brick veneer, CMU's, concrete aggregate, insulation, and others
  - Appearance of these materials can be modified to add aesthetic value

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[1] "Specifications for and Classification of Brick," The Brick Industry Association, Oct-2007.

Technology Background

- Technical and/or economic advantages:
  - Low temperature production
  - Low environmental impact
  - Low-cost fabrication
  - Easily tailorable properties
  - Flexible manufacturing
  - Performance meets ASTM requirements
  - Direct use of carbon ore in product
  - Utilizes abundant ND lignite resource
  - Can utilize REE extracted lignite and waste lignite
- Technical and/or economic challenges:
  - Initial bench scale development
  - Limited domestic sources of required additive
  - Feedstock prices and availabilities are highly dependent on global energy prices

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Technical Approach/Project Scope

- Project Scope of Work
  - **Task 1:** Project Management and Reporting
  - **Task 2:** Feedstock Procurement
  - **Task 3:** Production of Building Materials
  - **Task 4:** Product Testing and Analysis
  - **Task 5:** Technical and Economic Assessment
  - **Task 6:** LIG2 Aggregate Testing
- Success Criteria
  - Demonstrate the ability to successfully sinter carbon-ore to produce value-added carbon products and high strength building materials
  - Demonstrate the ability to produce 5-10 bricks/day
  - Complete a TEA, LCA, and concept design showing potential for technology to be profitable for the lignite industry

Technical Approach/Project Scope

Task / Subtask Number	Milestone Description	Planned Task Completion Date	Verification Method
✓ 1.1	Project Management Plan	10/31/2021	PMP File
✓ 1.1	Project Kick-off meeting	12/30/2021	Kick-off slides
1.1	Final Report	2/29/2024	Final Report File
✓ 1.2	Technology Maturation Plan (TMP)	12/30/2021	Initial TMP File
✓ 1.3	Workforce Readiness Plan (WRP)	9/30/2023	WRP File
✓ 1.4	Summary of Environmental Justice Considerations	12/30/2021	Initial Summary File
✓ 1.5	Summary of Economic Revitalization and Job Creation Outcomes	12/30/2021	Initial Summary File
✓ 1.6	Environmental, Safety, and Health Analysis	12/30/2021	Initial Summary File
✓ 1.7	Safety Management Plan (SMP)	10/31/2021	SMP File
✓ 2.0	Feedstock Procurement Report	12/31/2021	Quarterly Report
✓ 3.0	Identification of Optimum Processing Conditions	4/30/2022	Quarterly Report
✓ 4.0	SCBM Testing and Analysis Report	2/29/2024	Attachment to Final Report
✓ 5.1	Technical and Economic Assessment	2/29/2024	Attachment to Final Report
✓ 5.2	Technology Gap Analysis	2/29/2024	Attachment to Final Report
✓ 5.3	Conceptual Design	2/29/2024	Attachment to Final Report
✓ 5.4	Life Cycle Analysis	2/29/2024	Attachment to Final Report

Technical Approach/Project Scope

Perceived Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Financial Risks:				
Cost of Materials	Low	High	Low	Review cost of materials and identify alternatives as needed.
Underestimate level of effort required to complete the work	Low	High	Med	Continually track costs and schedule.
Cost Schedule Risks:				
Cost tracking	Low	High	Low	Assign responsibility for managing cost. Dedicated program resource manager for project management. Utilization of Project cost tracking system.
Technical Scope Risks:				
Availability of additive bonding materials	Low	High	Low	Project team has identified multiple sources of additive materials for additive bonding materials.
Operational consistency during testing	Medium	Medium	Medium	Work with plant operations and carbon ore delivery to maintain optimum test conditions to ensure quality data is obtained.
Management Planning and Oversight Risks:				
Equipment Availability	Medium	High	Medium	All equipment and sources of equipment to be purchased have been identified. Current supply chain delays will be monitored and may cause delays in receipt of equipment. Equipment will be purchased as soon as possible to mitigate any potential issues.
ES&H:				
Volatile organic compound release	Low	Low	Low	All gases and volatiles released during sintering will be released into a hood.

Progress and Current Status of Project

- **Task 1:** Project Management and Reporting
  - Regular internal team meetings, billing, budgeting, reporting
- **Task 2:** Feedstock Procurement
  - Identified optimal additives and carbon-ore types, resource availability, and estimated feedstock costs

Component	Cost ($/ton)
Waste Carbon-Ore	20
REE Extracted Carbon-Ore	110
Additive #2	1,283
Internal Lubricant	3,000
Additive #3	3,206
Additive #4	2,000
Additive #12	20
Binder #1	800
Coating	655

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Progress and Current Status of Project

- **Task 3:** Production of Building Materials
  - Necessary equipment for scaled-up production were identified, procured, and installed
    - Custom brick pressing die, Large furnace, 100-ton hydraulic press, Vibratory mill, Sieve shaker
  - Optimized feedstock and processing conditions
  - Characterized SCBM samples
    - Proximate, Ultimate, **Carbon content**, Gamma-ray emissions, Computer-controlled scanning electron microscopy (CCSEM), **Density**, Porosity (He-pycnometry), **Compressive strength**, and Hardness
  - Identified list of applications in which LIG2 products have the potential to be commercialized within 10 years
    - **Building brick**, Facing brick, Hollow brick, Thin veneer brick, Concrete aggregate, Concrete masonry units, Architectural block, and Insulation

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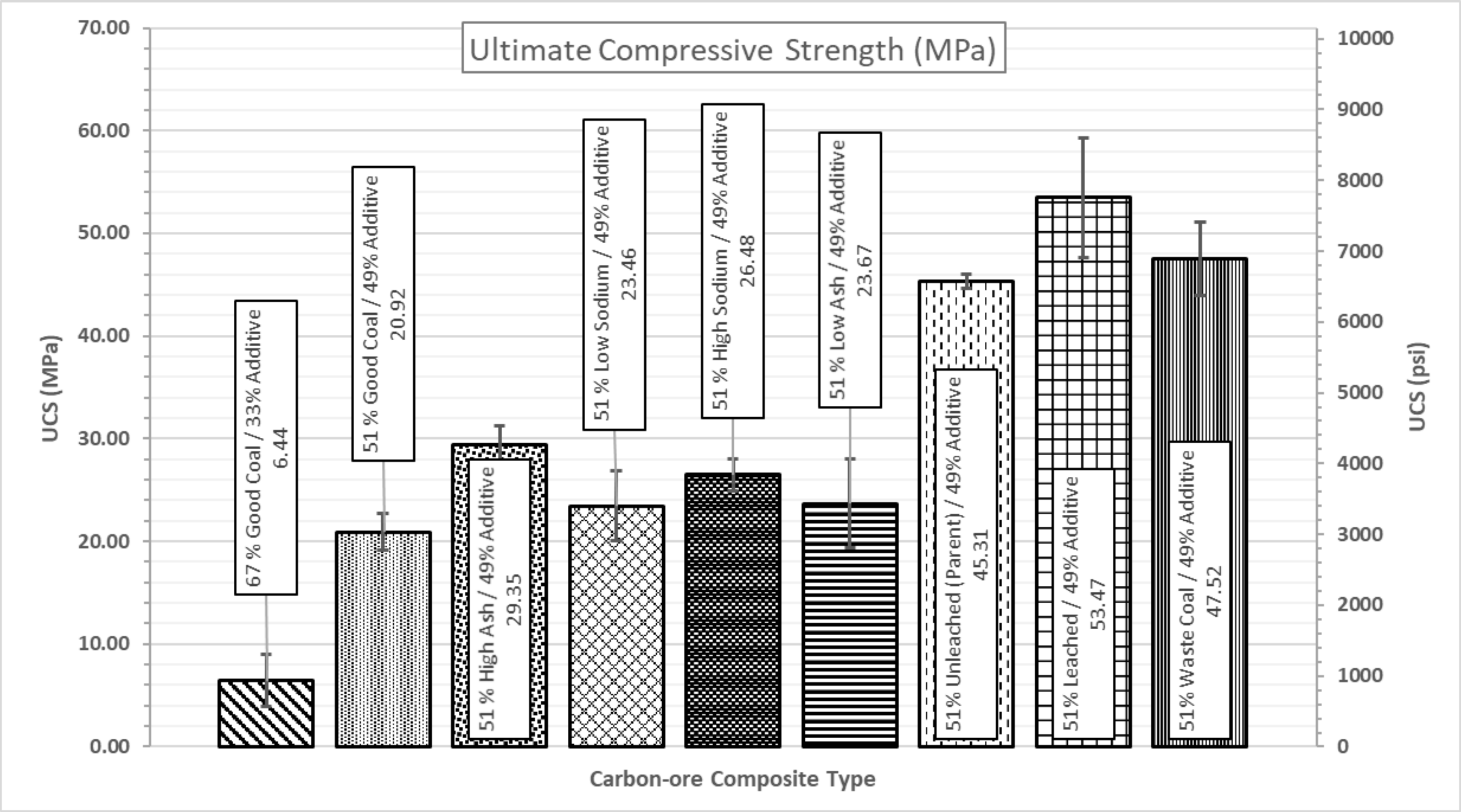
Progress and Current Status of Project



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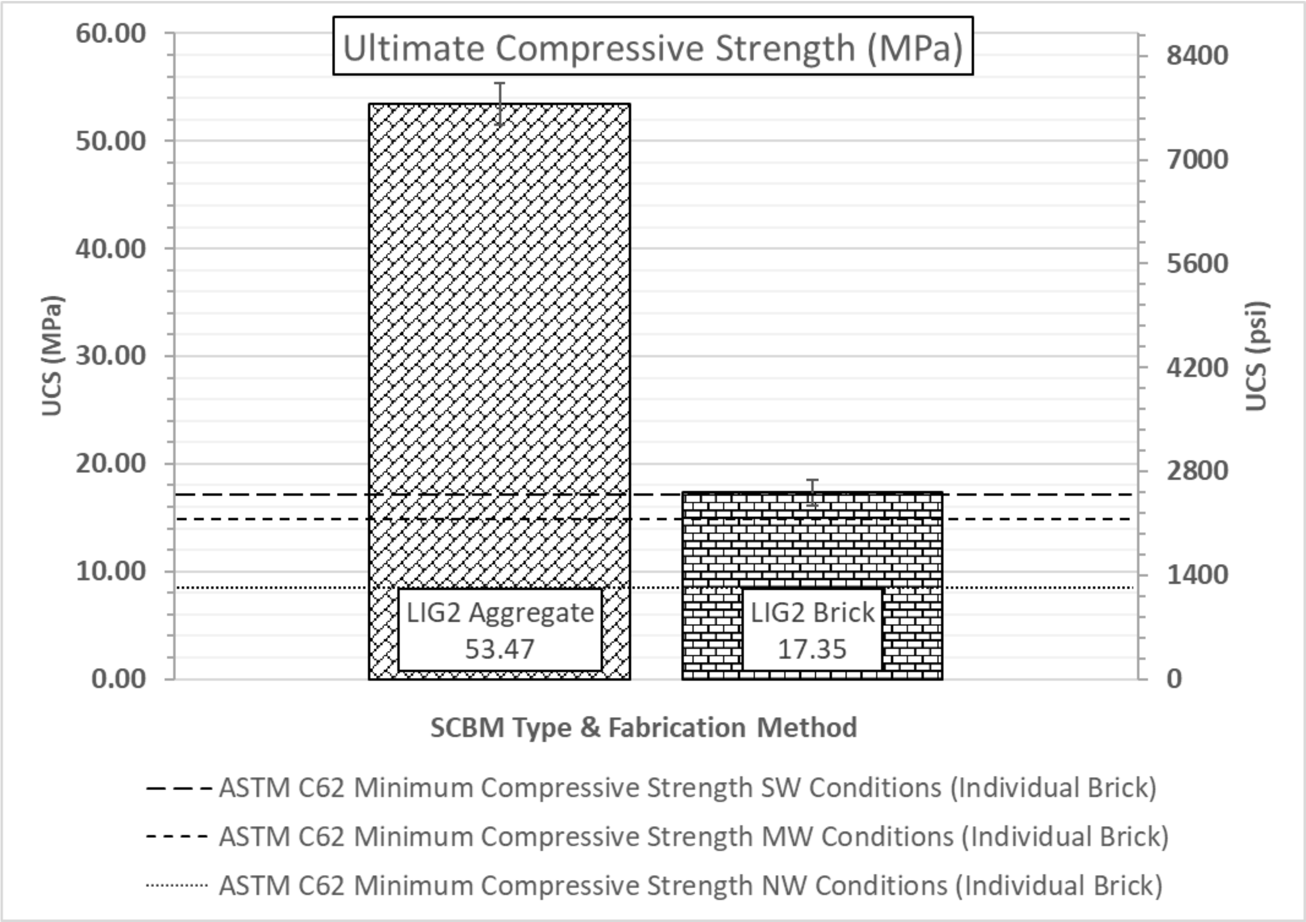
Progress and Current Status of Project

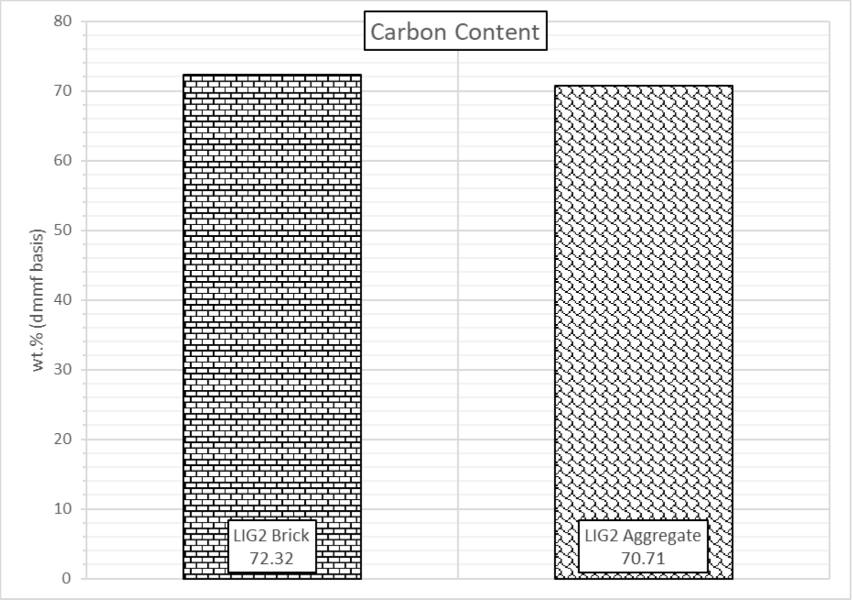
- SCBM Characterization: Compressive Strength



Progress and Current Status of Project

- SCBM Characterization: Carbon Content

	MTI 23-477 (post-sintered LIG2 brick)		
	As-received	Dry	Dry organic mineral matter-free (dmmf)
Ultimate (wt%)			
Total Moisture	3.39	-	-
Ash	15.86	16.42	-
Carbon	58.14	60.18	72.32
Hydrogen	4.04	3.79	4.55
Nitrogen	0.97	1.01	1.21
Total Sulfur	1.58	1.64	1.97
Oxygen by Difference	19.41	16.97	19.94



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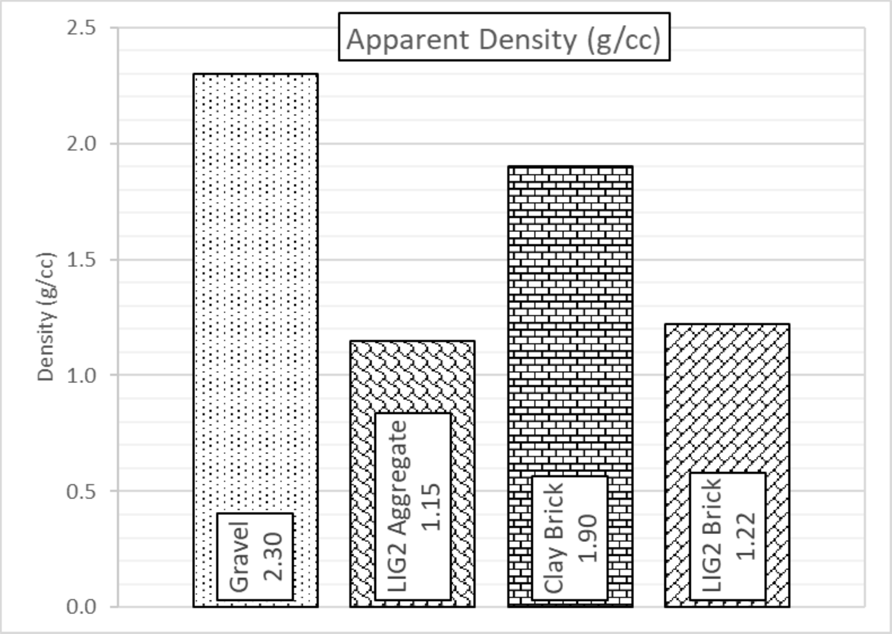
Progress and Current Status of Project

- SCBM Characterization: Density

Sample Type	Apparent Density (g/cc)	% Weight Decrease
Clay Brick[2]	1.90	-
LIG2 Brick	1.22	35.82%
Gravel[3]	2.30	-
LIG2 Aggregate	1.15	50.13%



[2] K. Ramesh and G. Viruthangiri, "Estimation of Porosity Values in Clay Bricks", *International Journal of Modern Research and Reviews*, September 2017.

[3] Kosmatka, Steven H. and Wilson, Michelle L., Design and Control of Concrete Mixtures, EB001, 15th edition, Portland Cement Association, Skokie, Illinois, USA, 2011, 460 pages.

Progress and Current Status of Project

- **Task 4:** Product Testing and Analysis
  - LIG2 brick manufacturing
  - Phase analysis and mechanical testing
    - Proximate, Ultimate, Carbon content, Fourier transform infrared spectroscopy (FTIR), SEM Morphology, SEM Phase Mapping, Density, Porosity (He-pycnometry), Tensile strength, **Compressive strength**, Flexural strength, Hardness, Wear, Wettability, **Thermal conductivity**, and Thermal expansion
  - Durability analysis
    - Antimicrobial growth, **Thermogravimetric analysis (TGA)**, Moisture absorption, Toxicity characteristic leaching procedure (TCLP)
  - Identification of candidate LIG2 products
    - **Building brick**, Facing brick, Hollow brick, and Insulation
  - Preliminary brick jointing

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Progress and Current Status of Project

Bench Scale Brickmaking Process

As-received waste carbon-ore materials

Step 1. Grinding

Step 2. Sieving

Step 3. Mixing

Step 4. Pressing

Step 5. Firing

Applications

- *Building brick,*
- *Facing brick,*
- *Brick veneer,*
- *Architectural block,*
- *Tiles,*
- *Insulation,*
- *and related materials*

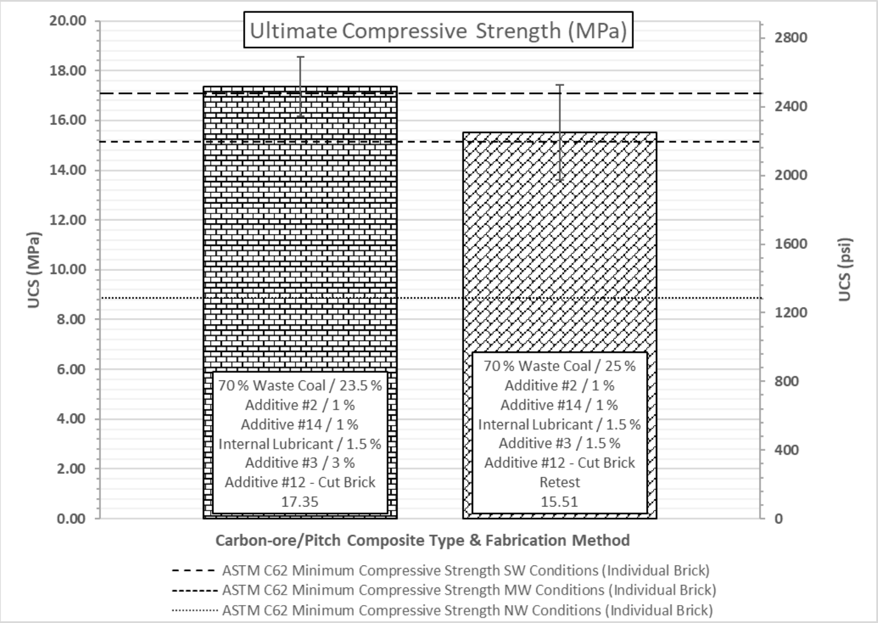
Final carbon-ore brick

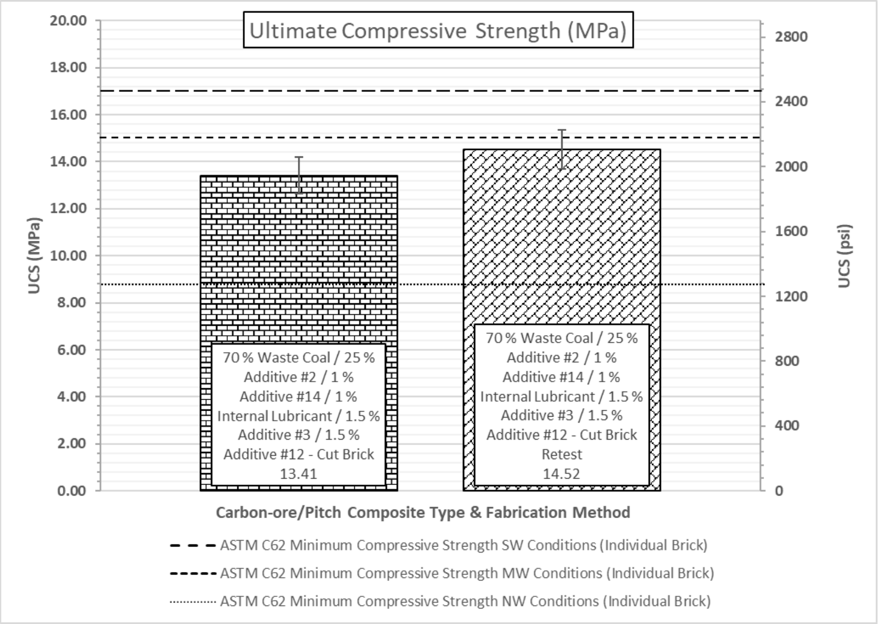
Next Steps

1. *Scale-up production to pilot scale.*
2. *Produce bricks at rate of 50-100 bricks per day.*

Progress and Current Status of Project

- LIG2 Brick Characterization: Compressive Strength





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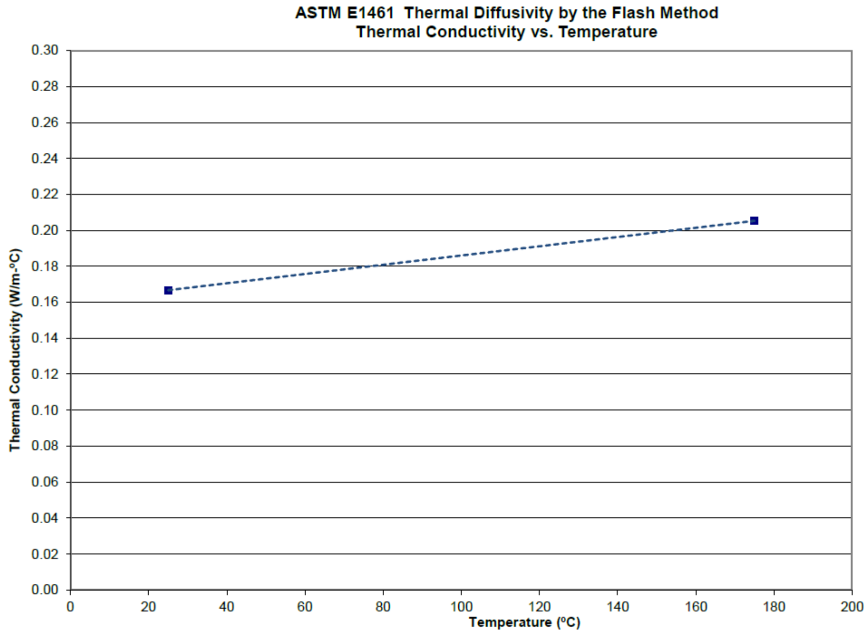
Progress and Current Status of Project

- LIG2 Brick Characterization: Thermal Conductivity

Sample ID	Density (g/cm^3)	Temperature (°C)	Diffusivity (cm^2/sec)	Specific Heat Capacity (J/g-°C)	Conductivity (W/m-°C)	Conductivity (BTU-in/hr-ft^2-°F)	Temperature (°F)
MTI 23-475	1.088	25	0.0014	1.087	0.17	1.16	77
		175	0.0011	1.700	0.21	1.42	347



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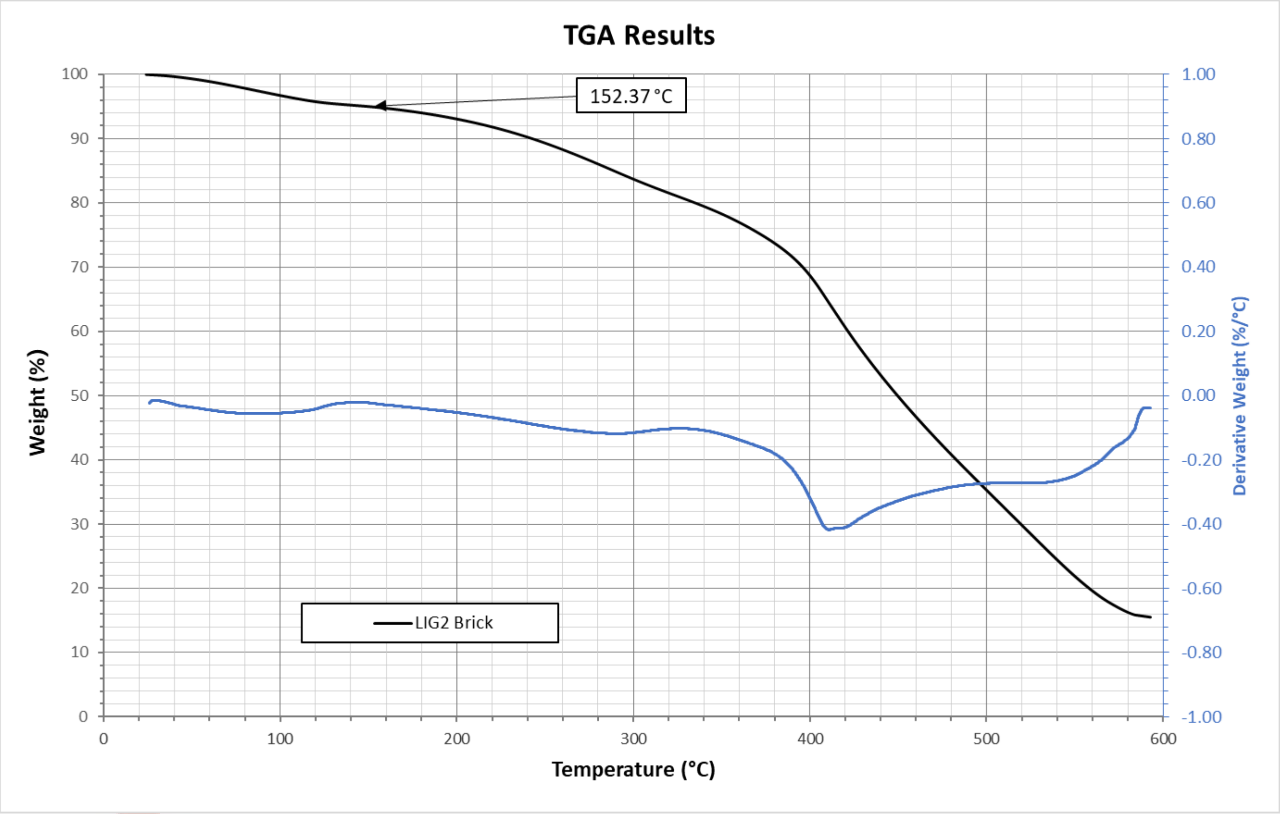
Progress and Current Status of Project

- LIG2 Brick Durability Analysis: TGA

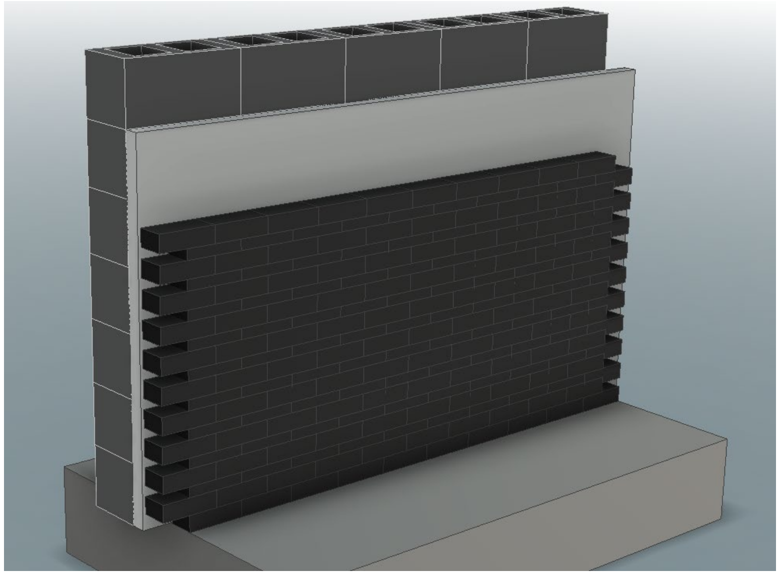


Progress and Current Status of Project

- Preliminary LIG2 Brick Jointing

Progress and Current Status of Project

- **Task 5:** Technical and Economic Assessment
  - Techno-Economic Assessment
  - Technology Gap Analysis
  - Conceptual Design
  - Lifecycle Analysis



Progress and Current Status of Project

- Technical and Economic Assessment

LCOP Component	LCOP	
$TVOM_n$	$	102,539,000
$TFOM_n$	$	21,038,000
TOC_n	$	4,460,000
TD_n	$	645,000
$TASC/TOC_{nominal}$		1.147
$TASC/TOC_{real}$		1.089
Product Units per Year	Units	6,600,000
$LCOP_{nominal}$	$/unit	1.59
$LCOP_{real}$	$/unit	1.51

LCOP = Levelized cost of product ($/unit)
TCP = Total cost of product ($)
$TVOM_n$ = Total variable O&M ($), including fuel costs, if any in year n
$TFOM_n$ = Total fixed O&M in year n ($)
TOC_n = Total overnight cost in year n ($)
TD_n = Total depreciation in year n ($)

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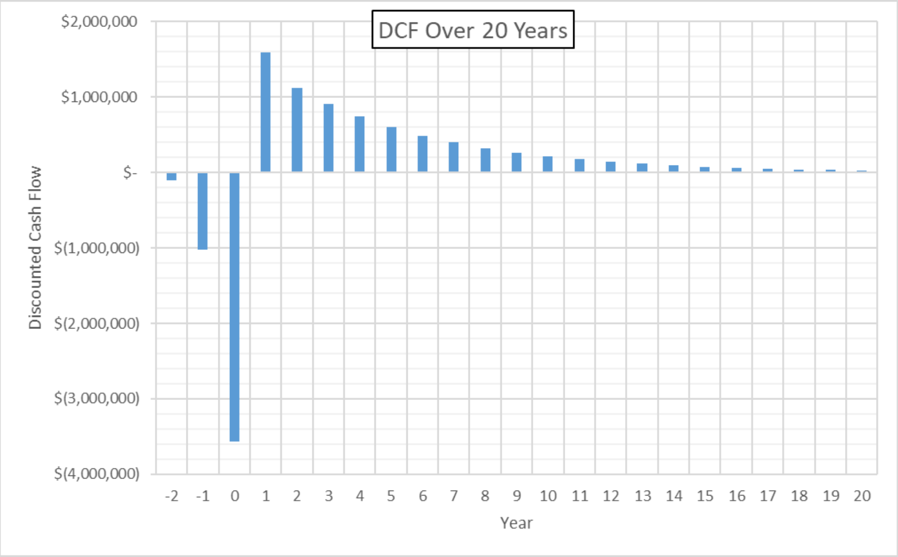
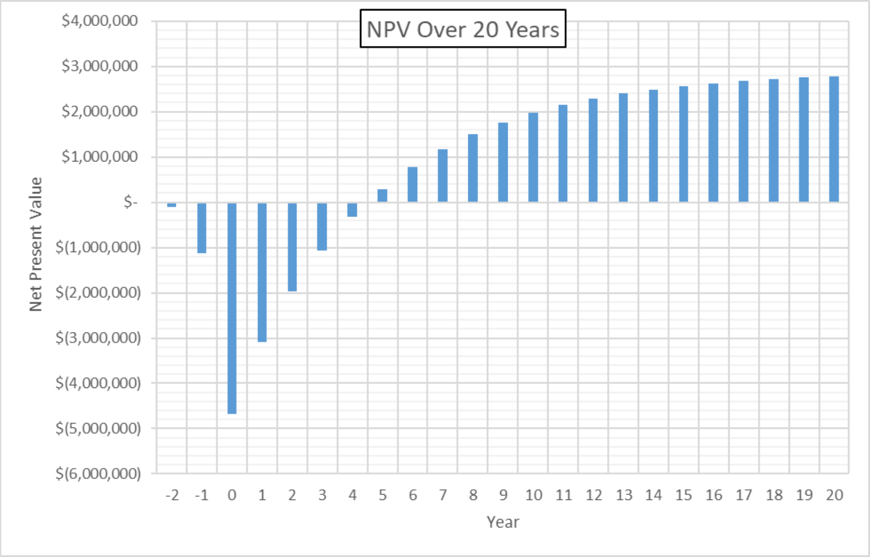
Progress and Current Status of Project

- Technical and Economic Assessment





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Progress and Current Status of Project

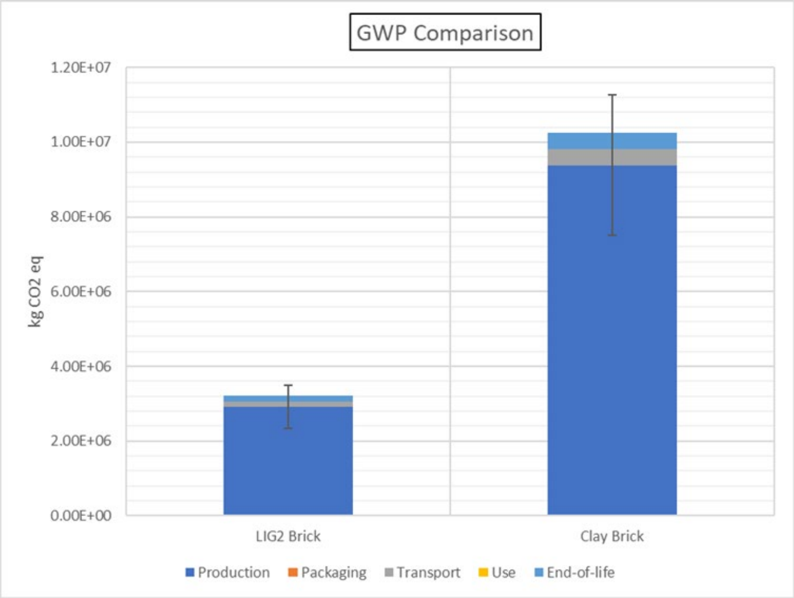
- Technology Gap Analysis

Technology Gap and Risk	Risk Mitigation	Development Pathway
Complete product characterization	Conduct remaining characterization	Identify remaining properties, and their requirements, necessary for building code certification.
Product improvement	Conduct additional R&D	Determine and improve any product weaknesses with respect to competitive products.
Product building code certification	Conduct additional R&D and receive product building code certification	Determine and improve any product weaknesses with respect to building code certification. Determine pathway to building code certification with reputable certification authority.
Feedstock quality	Conduct additional R&D and develop feedstock quality management system	Discuss potential feedstock variabilities with suppliers. Conduct testing and analysis of feedstock variations.
Production capability	Design and select equipment appropriate for LIG2 brick production	Investigate equipment material handling capabilities. Work closely with equipment manufacturers to ensure equipment performance matches expectations. Test purchased equipment to verify equipment capability to produce LIG2 bricks.
Production quality	Employ quality control methods	Identify factors contributing to variations in LIG2 brick production. Conduct R&D to determine acceptable parameters for each factor. Establish quality control methods based on R&D results.
Performance of commercial equipment	Design and select equipment appropriate for LIG2 brick production	Investigate equipment material handling capabilities. Work closely with equipment manufacturers to ensure equipment performance matches expectations. Test purchased equipment to verify satisfactory performance.

Progress and Current Status of Project

- Lifecycle Analysis

Comparative kg CO_2-eq balance	LIG2 Brick	Traditional Clay Brick	Ratio	Percent decrease in CO_2-eq emissions
Production	2.91E+06	9.38E+06	0.31	69.0%
Packaging	1.26E+02	1.73E+02	0.73	27.2%
Transport	1.45E+05	4.23E+05	0.34	65.8%
Use	0.00E+00	0.00E+00	-	-
End-of-life	1.70E+05	4.49E+05	0.38	62.1%
Total	3.23E+06	1.03E+07	0.31	68.5%



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Progress and Current Status of Project

- **Task 6:** LIG2 Aggregate Testing
  - LIG2 aggregate and concrete production
  - LIG2 aggregate testing
  - LIG2 aggregate SEM and phase analysis

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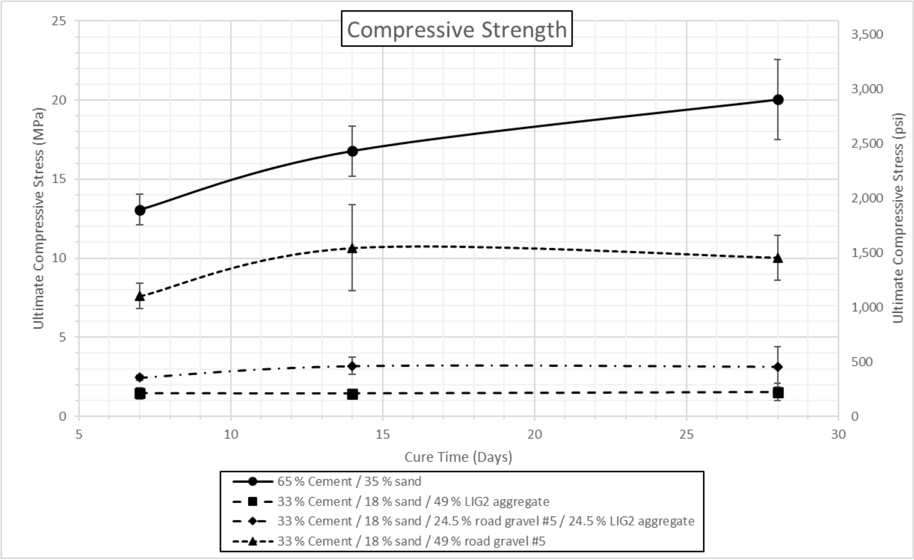
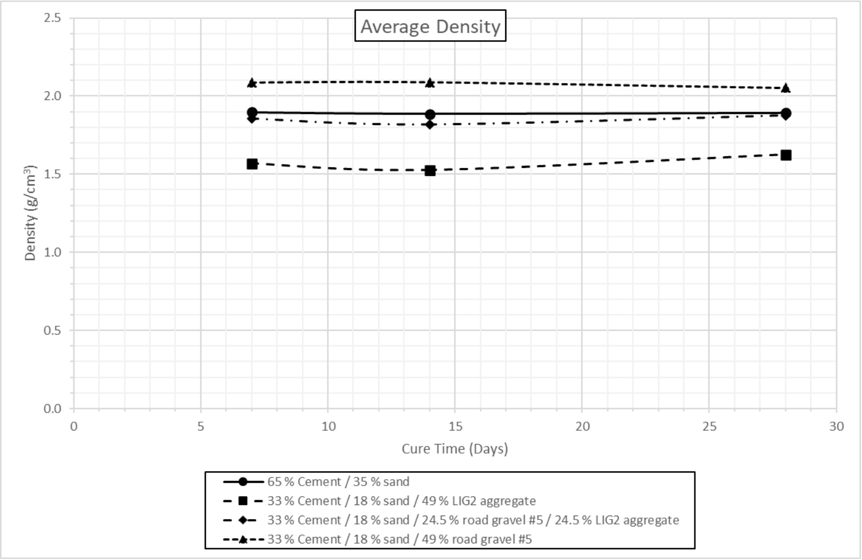
Progress and Current Status of Project

- LIG2 Aggregate Testing





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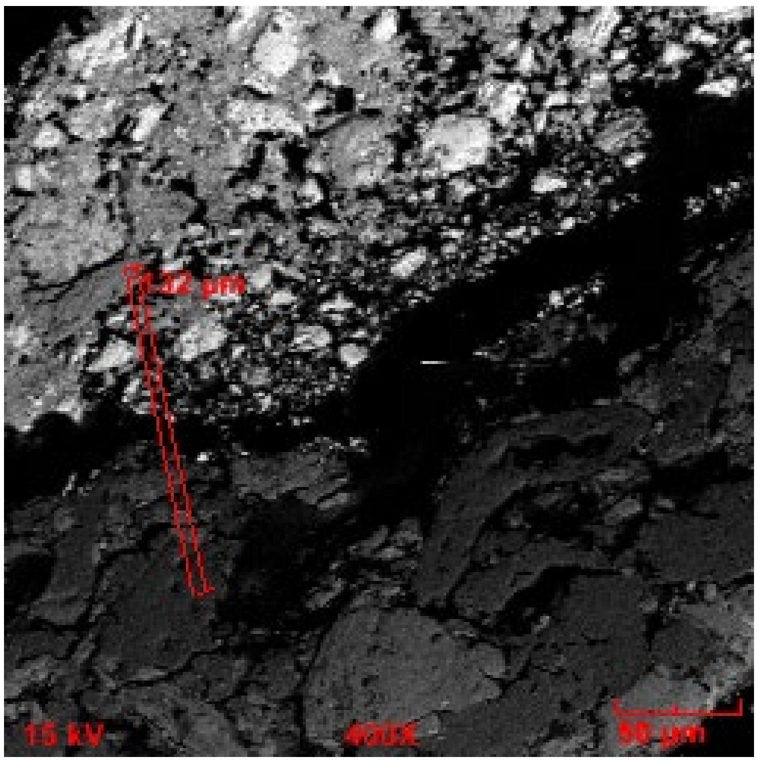
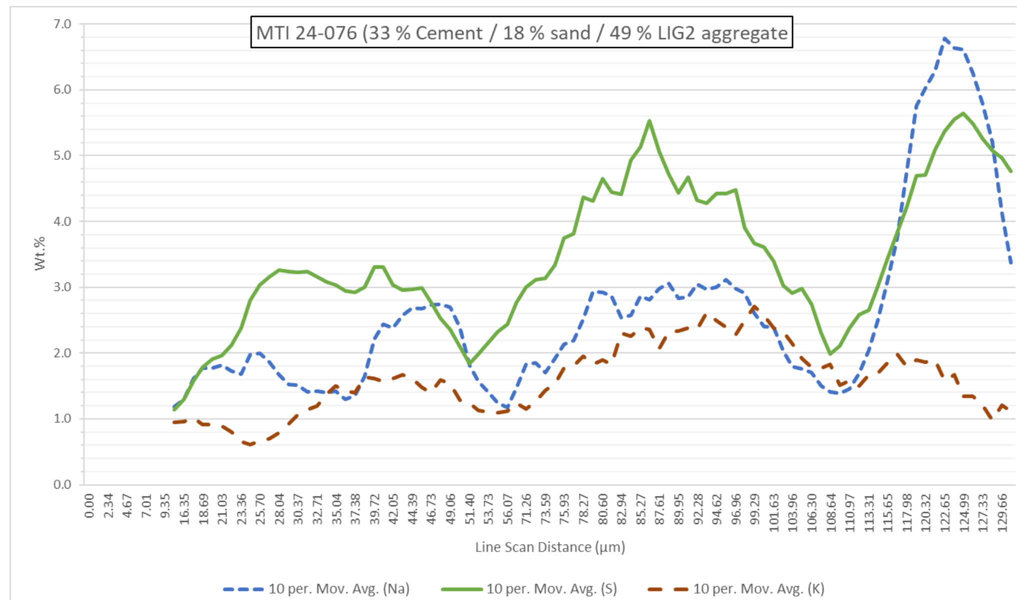
Progress and Current Status of Project

- LIG2 aggregate SEM and phase analysis





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Progress and Current Status of Project

- Performance levels achieved thus far include:
  - ✔ Develop value-added products from carbon ore
  - ✔ Carbon ore building materials will contain ≥70 wt.% carbon and ≥51 wt.% of carbon from carbon ore
  - ✔ Demonstrate the ability to produce Sintered Carbon Ore Building Materials (SCBM)
  - ✔ Ultimately to produce 5-10 bricks per day
  - ✔ Complete a Technical and Economic Analysis (TEA), a Technology Gap Analysis, and a Life Cycle Analysis (LCA) on the LIG2 brick process
  - ✔ Create a conceptual design of a carbon-based building used LIG2 products
- Economic and technical advantages of project performance:
  - Utilization of vast lignite resource
  - Use of low-cost, abundant raw materials
  - Production of value-added (LIG2) products from unused carbon ores
  - Meets and exceeds ASTM performance requirements
  - Support to REE and CM recovery processes
  - Environmentally friendly and "next-use" benefits
  - High paying, environmentally friendly jobs
  - Benefit to rural and underrepresented communities

Progress and Current Status of Project

- Synergistic opportunities of this project include:
  - "Rare Earth Element Extraction and Concentration at Pilot-Scale from North Dakota Coal-Related Feedstocks" DE-FE0031835
  - "Production of Germanium and Gallium concentrates for Industrial Processes" DE-FE0032124
  - "Recovery & Refining of Rare Earth Elements from Lignite Mine Wastes" DE-FE0032295
  - "Production of Germanium and Gallium Concentrates for Industrial Processes" DE-FOA-0002619
  - "Enhancing the Economics of Critical Minerals Production from Lignite Through Value-Added Carbon Products" DE-FOA-0003105
  - "Lignite-Derived Hard Carbon as Na-Ion Battery Anodes" DE-FOA-0003202

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Plans for Future Testing/Development/ Commercialization

- In this project:
  - N/A
- After this project:
  - Further product optimization and characterization
  - Pilot scale production (50-100 bricks/day)
  - Building code compliance evaluation and certification
  - Design and construction of LIG2 brick building
- Commercial scale-up potential:
  - Scale-up and identification of mass-production pathways
  - Identification of target markets and fit-for-use production
  - Marketing and securement of preliminary contracts
  - Design, construction, and operation of commercial facility

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Outreach and Workforce Development Efforts/Achievements

- Outreach
  - Public news release[4]
- Workforce Development
  - Provided training to produce sintered carbon-ore building materials (SCBM) samples for employees at MTI and postdoc, graduate, and undergraduate students at UND
  - Provided opportunities for individual study and experience in materials science, carbon-ore and biomass processing, bench scale manufacturing, advanced characterization techniques, and techno-economic and lifecycle analyses

[4] "Grand Forks-based company awarded $499K from U.S. energy department to use coal as building materials", Grand Forks Herald, https://www.grandforksherald.com/business/grand-forks-based-company-awarded-499k-from-u-s-energy-department-to-use-coal-as-building-materials, June 2021.

Summary Slide

- The SCBM technology is a groundbreaking technology that demonstrates that lignite coal particles can be successfully sintered at relatively low temperatures to produce a high-strength building material
  - Laboratory findings have shown SCBM's to meet and exceed ASTM brick requirements for compressive strength
  - Capable of producing products that meet or exceed building materials requirements while maintaining ≥70 wt.% carbon and ≥51 wt.% carbon coming from carbon-ore
  - Demonstrate the technical and economic flexibility of the SCBM technology
- Future projects will continue development and refinement LIG2 brick production at the pilot scale and above
- SCBM technology can valorize waste and REE extracted carbon-ores providing value-added opportunities for the carbon-ore industry

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Acknowledgements

- DOE/NETL
  - Project Manager: Mark Render
- Microbeam Technologies
  - Logan Anderson, Dr. Steve Benson, Alex Benson
- University of North Dakota
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  - Nolan Theaker
- North American Coal Corporation
  - Gerard Goven
- North Dakota Industrial Commission/Lignite Energy Council
  - Mike Holmes

MICROBEAM TECHNOLOGIES, INC.

Thank You

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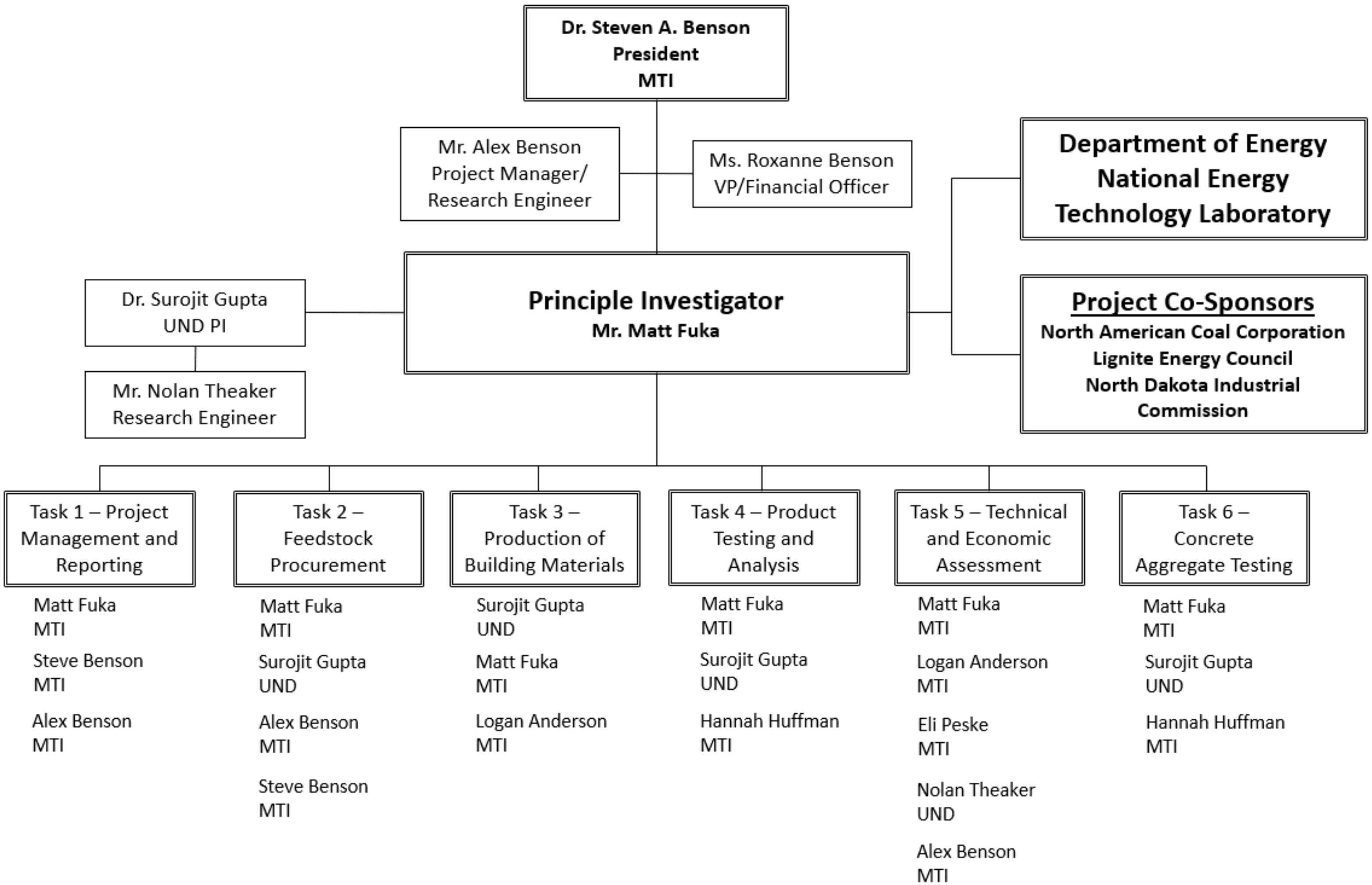
MICROBEAM TECHNOLOGIES, INC.

Appendix

Organization Chart

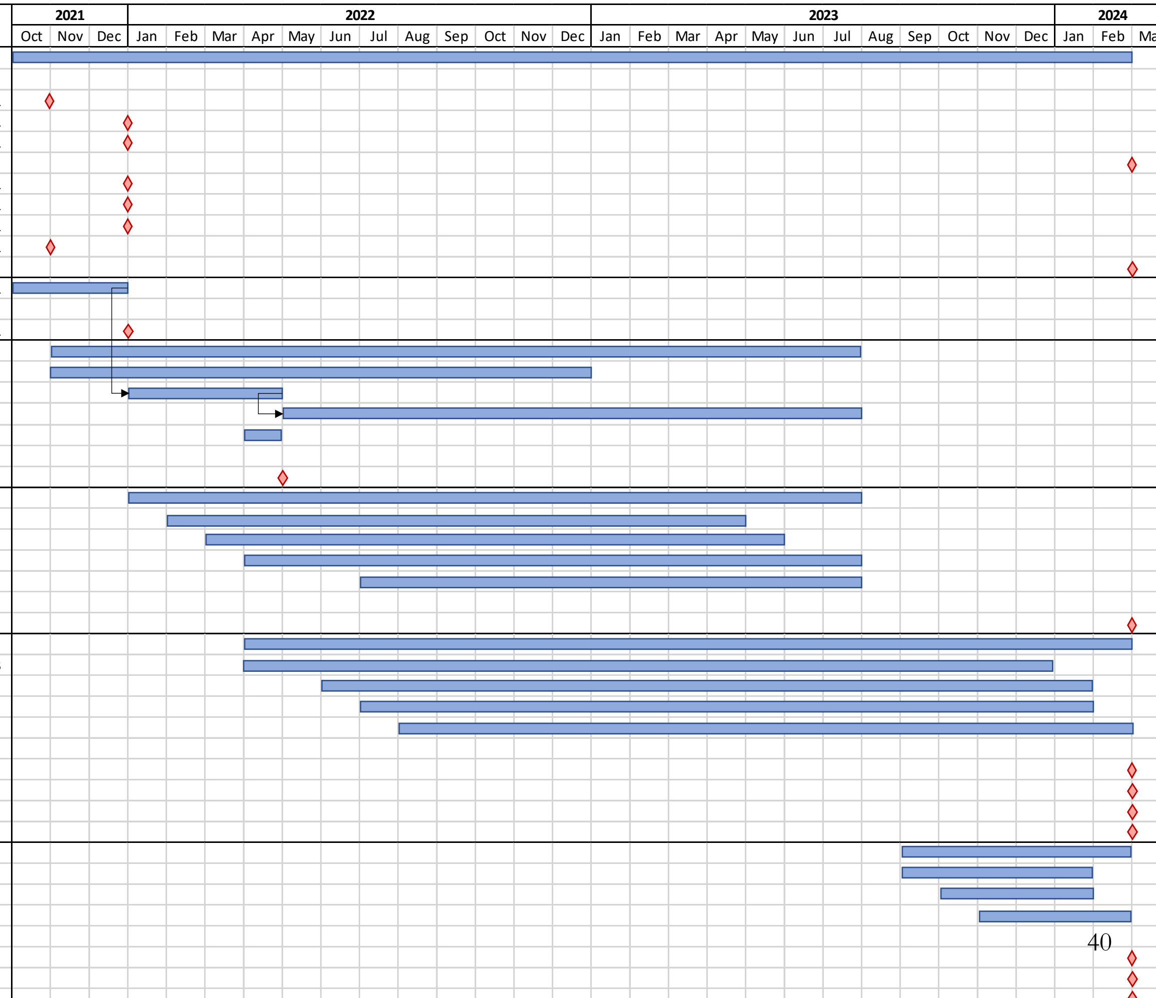
- Project Team:
  - Microbeam Technologies Inc. (Lead)
  - University of North Dakota
- Support From:
  - U.S. DOE/NETL
  - North American Coal Corporation
  - North Dakota Industrial Commission/Lignite Energy Council

Organization Chart



Gantt Chart

Task/Subtask Name	Start Date	End Date
Task 1 - Project Management and Reporting	10/1/2021	3/29/2024
Milestones		
Project Management Plan (PMP)		10/31/2021
Project Kickoff Meeting		12/30/2021
Technology Maturation Plan (TMP)		12/30/2021
Workforce Readiness Plan (WRP)		3/29/2024
Summary of Environmental Justice Considerations		12/30/2021
Summary of Economic Revitalization and Job Creation Outcomes		12/30/2021
Environmental, Safety, and Health Analysis		12/30/2021
Safety Management Plan (SMP)		10/31/2021
Final Report		3/29/2024
Task 2 - Feedstock Procurement	10/1/2021	12/31/2021
Milestones		
Feedstock Procurement Report		12/31/2021
Task 3 - Production of Building Materials	11/1/2021	7/31/2023
Subtask 3.1 - Equipment Set-up	11/1/2021	12/1/2022
Subtask 3.2 - Optimization of Processing Conditions	12/1/2021	4/30/2022
Subtask 3.3 - Production of Testing Quantities	5/1/2022	7/31/2023
Subtask 3.4 - Identification of Commercializable LIG2 Products	4/1/2022	4/30/2022
Milestones		
Identification of Optimum Processing Conditions		4/30/2022
Task 4 - Product Testing and Analysis	12/1/2021	7/31/2023
Subtask 4.1 - Phase Analysis and Mechanical Testing	1/1/2022	4/30/2023
Subtask 4.2 - Scanning Electron Microscopy (SEM) Analysis	2/1/2022	5/31/2023
Subtask 4.3 - Durability Analysis	4/1/2022	7/31/2023
Subtask 3.4 - Identification of Candidate LIG2 Products	7/1/2022	7/31/2023
Milestones		
LIG2 Testing and Analysis Report		3/29/2024
Task 5 - Technical and Economic Assessment	4/1/2022	3/29/2024
Subtask 5.1 - Techno-Economic Assessment	4/1/2022	12/31/2023
Subtask 5.2 - Technology Gap Analysis	6/1/2022	1/31/2024
Subtask 5.3 - Conceptual Design	7/1/2022	2/29/2024
Subtask 5.4 - Life Cycle Analysis of Products	8/1/2022	3/29/2024
Milestones		
Technical and Economic Assessment		3/29/2024
Technology Gap Analysis		3/29/2024
Conceptual Design		3/29/2024
Life-Cycle Analysis		3/29/2024
Task 6 - LIG2 Aggregate Testing	9/1/2023	3/29/2024
Subtask 6.1 – LIG2 Aggregate Production	9/1/2023	1/31/2024
Subtask 6.2 – Performance of LIG2 Aggregate in Concrete	10/1/2023	2/29/2024
Subtask 6.3 – SEM Analysis of LIG2 Aggregate in Concrete	11/1/2023	3/29/2024
Milestones		
Technical and Economic Assessment		3/29/2024
Technology Gap Analysis		3/29/2024
Life-Cycle Analysis		3/29/2024



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